THE CHRONOLOGY OF THE PERMIAN AND TRIASSIC OF DEVON AND SOUTH-EAST CORNWALL (U.K.): A REVIEW OF METHODS AND RESULTS

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A combination of isotopic dating, biostratigraphy and magnetostratigraphy allows post-Variscan to pre-Jurassic formations in Devon and south-east Cornwall to be related to the international Permian and Triassic stages with varying degrees of precision. Isotopic dates from volcanic rocks in the lower part of the Exeter Group are Early Permian (Asselian to Artinskian) in age, consistent with the reverse polarities obtained from palaeomagnetic studies. The upper part of that group has yielded pollen that indicate a maximum age of Mid Permian (Roadian(?) or Wordian), and a few palaeomagnetic results, mostly with reverse polarity, that may suggest a pre-Illawara Reversal (pre-Capitanian) age. The magnetostratigraphy of the overlying Aylesbeare Mudstone Group indicates a post-Illawara Reversal (post-Wordian) age. That of the succeeding Sherwood Sandstone Group indicates ages ranging from late Olenekian (late Early Triassic), or older, in the lower part of the group, to early Mid Triassic (Anisian) in its upper part. The magnetostratigraphy of the overlying Mercia Mudstone Group indicates ages ranging from latest Anisian, in the lowest beds, through the late Mid Triassic (Ladinian) and early Late Triassic (Carnian), into the mid Late Triassic (Norian). The magnetostratigraphic evidence is compatible with macrofossil evidence of an Anisian age from the Otter Sandstone Formation, and palynological evidence of Carnian and younger Late Triassic ages from the Mercia Mudstone Group. The Penarth Group and basal Lias Group are Rhaetian (latest Triassic) in age, based on both bio- and magneto-stratigraphic evidence.

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INTRODUCTION

The stage and series nomenclature currently used for the Triassic System was adopted by the Subcommission on Triassic Stratigraphy in 1992 (Baud, 1992); that used for the Permian System was adopted by the Subcommission on Permian Stratigraphy in 1996 (Jin Yu-gan *et al.*, 1997). A Global Stratotype Section and Point (GSSP) is required for the formal definition, in a basal boundary stratotype, of each stage. This process is incomplete; of the 17 boundaries involved, only eight have GSSPs ratified by the IUGS International Commission on Stratigraphy (ICS) (Table 1).

Ages have been assigned to all the stage boundaries (Table 1) but the geochronological control on this presently incompletely defined chronostratigraphy is imperfect. Satisfactory dates (e.g. U-Pb SHRIMP, TIMS or IDTMS dates from zircons from biostratigraphically well-controlled tuffs) are only available from levels in the highest Gzhelian to middle Asselian, upper Sakmarian, upper Wordian, middle Changhsingian to lower Induan, middle to upper Anisian, upper Ladinian and upper Rhaetian successions (Menning, 2001; Ogg, 2004; Wardlaw *et al.*, 2004); other levels are poorly constrained.

THE SUCCESSION

The succession under consideration rests unconformably upon Devonian and Carboniferous rocks that were affected by the Variscan orogeny. It includes formations that constitute, in ascending order, the Exeter, Aylesbeare Mudstone, Sherwood Sandstone, Mercia Mudstone and Penarth groups, and the basal beds of the Lias Group (Warrington, 2004). This post-Variscan – pre-Jurassic succession is exposed in almost continuous sections on the south-east Devon coast, from Torbay to near Lyme Regis. The outcrop strikes northwards from the coast, through east Devon, into Somerset. Formations of the Exeter Group form a major westward extension of this outcrop in the Crediton Trough, with outliers farther west, and a smaller westward extension around Tiverton, bordered to the north by outliers. Isolated outliers of rocks of Exeter Group aspect occur at Portledge and Peppercombe in north Devon, at Slapton and Thurlestone in south Devon, and on the nearby Rame Peninsula in south-east Cornwall.

The means available for relating these deposits to the international chronostratigraphic scheme (Table 1) include isotopic dating, biostratigraphy and magnetostratigraphy. Only magnetostratigraphy (Opdyke and Channell, 1996) is potentially applicable to the complete succession; the application of isotopic dating is restricted to Permian formations with interbedded volcanic rocks, and that of biostratigraphy largely to formations of Triassic age. Macrofossils and trace fossils have been known from various levels in the succession for nearly 200 years, and microfossils and palynomorphs within the last 55 and 35 years respectively, mainly from Triassic formations. Palaeomagnetic work began in the early 1950's but magnetostratigraphic studies commenced only within the last ten years. Isotopic dating of volcanic rocks in the succession commenced about 45 years ago.

METHODS AND RESULTS

Isotopic dating

The possibility of using the amounts of the decay products of radioactive minerals to determine the age of the mineral was first clearly suggested by Rutherford in 1905 (Wager, 1964). In the succession under review its application is limited to the Exeter Volcanic Rocks. These are predominantly basaltic and lamprophyric lavas interbedded with continental deposits in the lower part of the Exeter Group around Exeter, in the Crediton Trough, and around Tiverton. Acid lava, though common as clasts in breccias, is rarely seen *in situ*; rhyolite occurs at Neopardy, in the Crediton Trough (Edwards and Scrivener, 1999), and in three small outliers on the Rame Peninsula, south-east Cornwall (Leveridge *et al.*, 2002).

The earliest isotopic studies were of a mica lamprophyre (minette) from Killerton, north of Exeter, at the east end of the Crediton Trough (Miller *et al.*, 1962), and a basalt from Dunchideock, south-west of Exeter (Miller and Mohr, 1964). Further analyses have been carried out on rocks from Killerton and from Knowle Hill, farther west in the Crediton Trough. All but two of the available dates were obtained by K/Ar analyses of whole-rock samples or separated biotites and have errors ranging from ±6 to ±11 my. The remaining dates are from Ar/Ar analyses by Chesley (reported by Scrivener, 1994) of biotites from a Killerton minette and an olivine microsyenite from Knowle Hill. The former, interbedded with the Thorverton Sandstone Formation (Edwards *et al.*, 1997), yielded a plateau age of 290.8±0.8 Ma; the latter, between the Bow Breccia and Knowle Sandstone formations (Edwards *et al.*, 1997), yielded a date of 281.8±0.8 Ma. In relation to a recent timescale for the Permian (Wardlaw *et al.*, 2004) these indicate, respectively, mid Sakmarian, and early Artinskian ages (Table 1). However, the sample from Knowle Hill shows secondary alteration, and may have lost argon (R. C. Scrivener, *pers. comm.*, September, 2005); the date from this lava must, therefore, be considered a minimum, and its age may be Sakmarian rather than Artinskian.

A K/Ar date of 290.7±6 Ma, obtained by Rundle from biotite from rhyolite at Kingsand, south-east Cornwall (Leveridge *et al.*, 2002), is the only one from a Permian acid volcanic rock in the region. In relation to the timescale of Wardlaw *et al.* (2004) it indicates a late Asselian to Sakmarian age (Table 1).

SYSTEM	SERIES	STAGE	GSSP STATUS[1]	AGE OF BASE (Ma)[2]
JURASSIC	Lower (part)	Hettangian	x	199.6
TRIASSIC	Upper	Rhaetian	x	203.6
		Norian	x	216.5
		Carnian	x	228
	Middle	Ladinian	2005	237
		Anisian	x	245
	Lower ('Scythian')	Olenekian	x	249.7
		Induan	2001	251
PERMIAN	Lopingian (Upper)	Changhsingian	2005	253.8
		Wuchiapingian	2004	260.4
	Guadalupian (Middle)	Capitanian	2001	265.8
		Roadian	2001	268
		Wordian	2001	270.6
	Cisuralian (Lower)	Kungurian	x	275.6
		Artinskian	x	284.4
		Sakmarian	x	294.6
		Asselian	1996	299
CARBONIFEROUS	Upper (part)	Gzhelian	x	303.9

Table 1. *Series and stage nomenclature and geochronology of the Permian and Triassic.* [1]*x – GSSP proposal awaited or awaiting vote; 0000 – date ratified by ICS.* [2]*from Ogg (2004) and Wardlaw* et al. *(2004).*

Magnetostratigraphy

Samples from the lowest *c.* 50 m of the Mercia Mudstone Group at Sidmouth, south Devon, were included in the first study of the palaeomagnetism of sedimentary rocks in the British Isles (Clegg *et al.*, 1954), and were investigated further by Creer (1957a). The palaeomagnetism of the Exeter Volcanic Rocks was studied first by Creer (1957b) and Creer *et al.* (1957), followed by Zijderveld (1967). In a more comprehensive study of these rocks, Cornwell (1967) documented a wider range of occurrences, including two on the Rame Peninsula, south-east Cornwall, together with sediments associated with the volcanic rocks and others from the Torbay Breccia and Dawlish Sandstone formations of the Exeter Group and the lower (Exmouth Mudstone and Sandstone) formation of the Aylesbeare Mudstone Group. These studies investigated fundamental aspects of palaeomagnetism and its application in the determination of polar wandering, latitudinal change and continental movement. Field reversals were recognised but the study of magnetostratigraphies based on sequences of normal and reversed polarity was a later development that has been applied to the succession under review only within the last ten years. The validity of field reversals noted in some of the earlier studies, which predated the adoption of the palaeomagnetic 'cleaning' methods developed in the 1960's, may be in doubt (M. W. Hounslow *pers. comm.*, November, 2005).

At the suggestion of the author, a magnetostratigraphic study of the Aylesbeare Mudstone Group was initiated in 1997 in connection with the British Geological Survey (BGS) survey of the Sidmouth district, and with the objective of resolving the position of the Permian – Triassic boundary. This study involved collaboration between the BGS and Dr M. W. Hounslow and other workers at the University of East Anglia, and was subsequently extended successively, under the direction of Dr R. A. Edwards (formerly BGS) and, latterly, the author, into the Exeter Group, the Sherwood Sandstone Group and finally the Mercia Mudstone Group, to connect with a separate study of the higher part of that unit (Posen *et al.*, 2001). Only the Sherwood Sandstone Group results have been fully documented (Hounslow and McIntosh, 2003).

The lower and upper parts of the Aylesbeare Mudstone Group have mostly normal and dominantly reverse polarities respectively (Hounslow *et al.*, 1998). The mostly normal sequence in the lower part of the group implies that it post-dates the Illawara Reversal. This event, at the top of the Mid Permian Wordian Stage, is dated at 265 Ma and separates the Permo-Carboniferous Reversed Superchron (or Kiaman Magnetic Interval), a long period of dominantly reverse polarity, from the Permo-Triassic Mixed Superchron (Menning, 2001). If this event occurs no higher than the base of the Aylesbeare Mudstone Group, it follows that the Exeter Group, which it overlies unconformably (Selwood *et al.*, 1984; Edwards and Scrivener, 1999), is no younger than Wordian. Comprehensive magnetostratigraphic documentation of the Exeter Group is not available but a pre-Illawara Reversal age is supported by the reverse polarities recorded from Exeter Volcanic Rocks (Cornwell, 1967; Zijderveld, 1967), and from sediments from the lower and, with one exception, the upper parts of the group (Cornwell, 1967).

The Aylesbeare Mudstone Group is succeeded unconformably by the Sherwood Sandstone Group, the lower formation of which, the Budleigh Salterton Pebble Beds, is succeeded unconformably by the Otter Sandstone Formation, the upper formation seen in the group on the south Devon coast. At outcrop the junction is marked by a layer of dreikanter overlying a palaeosol (Wright *et al.*, 1991) and is apparently a disconformity. However, at subcrop in west Dorset, an angular unconformity is recognised between the Otter Sandstone Formation and underlying units (Butler, 1998); the latter include the Budleigh Salterton Pebble Beds and a younger argillaceous unit that is preserved only locally between that formation and the Otter Sandstone Formation at subcrop. An Anisian age was proposed for the Otter Sandstone Formation, and an Olenekian (late Early Triassic) or Spathian (late Olenekian) to Aegean (earliest Anisian) age (Hounslow *et al.*, 2000; Hounslow and McIntosh, 2003) for the Budleigh Salterton Pebble Beds. However, the ages proposed for the latter may not adequately reflect the evident magnitude of the sub-Otter Sandstone Formation unconformity, which represents the time taken for deposition of the concealed argillaceous unit and subsequent folding and erosion; consequently, the Budleigh Salterton Pebble Beds may be older.

The position of the Permian-Triassic boundary in the succession is unresolved. Comparison of the Aylesbeare Mudstone Group polarity sequence with those illustrated by Wardlaw *et al.* (2004, figure16.1) and Ogg (2004, figure17.1) suggests that correlation is possible with the Capitanian to basal Wuchiapingian, the higher Wuchiapinigian to Changhsingian, or the Induan to higher Olenekian. The first and second possibilities would place the boundary above the Aylesbeare Mudstone Group, with the first allowing a substantial interval between the deposition of that group and of the Otter Sandstone Formation, that would accommodate the deposition of the Budleigh Salterton Pebble Beds and the time represented by the unconformities below and above that formation. The second would allow a shorter interval of time to accommodate the same events and imply that the unconformity below the Aylesbeare Mudstone Group represents Capitanian and earliest Wuchiapingian time. The third possibility would place the boundary below the Aylesbeare Mudstone Group and appears least likely, as it would imply a substantial gap between the Exeter and Aylesbeare Mudstone groups, and require the post-Budleigh Salterton Pebble Beds – pre-Otter Sandstone Formation deposition, folding and erosion to be accomplished in a very short period of time.

The magnetostratigraphy of the Otter Sandstone Formation is largely comparable with that of independently dated marine Anisian successions (Hounslow and McIntosh, 2003). However, the Ladinian GSSP (Table 1) has been placed at the base of the *curionii* ammonite zone and the correlative level in the Devon succession, based on magnetostratigraphy, is in the lower part of the Mercia Mudstone Group, at the highest of the three potential boundary levels illustrated by Hounslow and McIntosh (2003, figure 12).

Formations that constitute the Mercia Mudstone Group are, in ascending order: a thick, predominantly red-brown mudstone unit; a thin, largely grey-green, fossiliferous unit of mudstones, siltstones and dolomitic sandstones; a second thick, predominantly red-brown mudstone unit, with prominent sulphate evaporites; and a second thin, mainly grey-green mudstone and siltstone unit (Warrington, 2004). The lower and upper red-brown units, the Sidmouth Mudstone and Branscombe Mudstone formations of Gallois (2001) respectively, were previously un-named in this area. The lower and upper grey-green units are, respectively, the Arden Sandstone and Blue Anchor formations of Warrington *et al.* (1980) (Howard *et al.*, in press). The magnetostratigraphy of this succession suggests that the Ladinian/Carnian boundary is near the top of the Sidmouth Mudstone Formation (Hounslow *et al.*, 2001, 2003). The position of the Carnian/Norian boundary has been interpreted as in the Branscombe Mudstone Formation (Hounslow *et al.*, 2001) or (Hounslow *et al.*, 2003) in the upper part of the underlying Dunscombe Mudstone Formation of Gallois (2001), in beds that he suggested correlate with or are older than the Arden Sandstone Formation. The Norian/Rhaetian boundary may be near the top of the Branscombe Mudstone Formation (Hounslow *et al.*, 2001) or higher (Hounslow *et al.*, 2004).

Biostratigraphy

The Exeter Group has yielded only a very small number of fossils, few of which are of stratigraphic value. Those from formations in the lower part of the group include burrows (*Beaconites*) in the Torbay Breccia Formation (Leveridge *et al.*, 2003) at Goodrington, Torbay (Laming, 1970; Ridgway, 1974; Pollard, 1976) and the Sandway Cellar Conglomerate Member of the Kingsand Rhyolite Formation at Kingsand, southeast Cornwall (Leveridge *et al.*, 2002; Bristow, 2004); similar structures are reported from Portledge, north Devon (Gayer and Cornford, 1992). They record the presence of an animal adapted to a harsh continental environment, and imply the existence of a food chain, the only other traces of which, rhizocretions at Portledge (Burley and Cornford, 1998) and a possible coprolite from Kingsand (Thomas, 2003), are of no stratigraphical value.

Formations in the upper part of the Exeter Group (Edwards *et al.*, 1997; Edwards and Scrivener, 1999) have yielded pollen, burrows and other trace fossils. The pollen, from beds below the Dawlish Sandstone Formation (Warrington and Scrivener, 1988, 1990; Edwards *et al.*, 1997; Edwards and Scrivener, 1999), include *Lueckisporites virkkiae*, which elsewhere ranges from Roadian(?) or Wordian beds, equivalent to part of the former 'Upper Permian' Kazanian Stage in Russia, to the highest Permian (Changhsingian). This palynological evidence indicates that the Whipton Formation and others, below the Dawlish Sandstone, that have yielded the same microflora, are no older than Roadian(?) or Wordian (early(?) to mid Mid Permian). The Watcombe Formation (Leveridge *et al.*, 2003), a potential correlative of the Whipton Formation, contains smaller examples of the burrows present in the lower part of the group at Goodrington (Laming, 1966; Selwood *et al.* 1984). Vertebrate tracks from the Dawlish Sandstone Formation near Exeter (Clayden, 1908a, b; Warrington and Scrivener, 1990; Edwards and Scrivener, 1999) are referable to *Chelichnus*, an ichnogenus found also in Permian continental formations in Scotland and in the Cornberger Sandstein in Germany, and regarded as restricted to the 'Later Permian' (McKeever and Haubold, 1996). Menning (1995) placed the Cornberger Sandstein above the level of the Illawara Reversal. The tracks from the Dawlish Sandstone Formation are testimony to a land fauna and imply the existence of a food chain, the only other indications of which, 'tracings of annelides, the clawlike feet marks of two species of small crustaceans, and obscure impressions of other objects' (Shapter, 1842), are of no stratigraphical value.

The Aylesbeare Mudstone Group is devoid of stratigraphically useful fossils; only reworked Devonian and Carboniferous spores (Warrington, 1971; Owens, 1972), and burrows and indeterminate plant debris (Henson, 1970; Selwood *et al.*, 1984) have been recorded.

In the Sherwood Sandstone Group, the Budleigh Salterton Pebble Beds lack indigenous fossils but include clasts that contain Ordovician and Devonian remains (Cocks, 1993). The succeeding Otter Sandstone Formation contains numerous levels of rhizocretions (Purvis and Wright, 1991; Hounslow and McIntosh, 2003) that indicate the existence of a prolific *in situ* flora, but no spores, pollen, or stratigraphically useful plant remains have been recovered. This formation has, however, yielded invertebrate and vertebrate fossils, the latter including fish, amphibians and reptiles (Paton, 1974; Milner *et al.*, 1990; Benton *et al.*, 2002; Spencer and Storrs, 2002). The vertebrate fauna indicates an Anisian (early Mid Triassic) age, compatible with the results of a magnetostratigraphic study (Hounslow and McIntosh, 2003).

The only stratigraphically useful fossils known from the Mercia Mudstone Group are palynomorphs recovered from the coast sections and the nearby Lyme Regis Borehole. The lower *c.* 155 m of the Sidmouth Mudstone Formation has proved barren (Warrington, 1971, 2002). Assemblages of spores and pollen (miospores) of Carnian (early Late Triassic) age have been recovered from beds higher in that formation and in the overlying Arden Sandstone Formation (Warrington, 1971, 1997, 2002; Fisher, 1972, 1985, *in* Jeans, 1978). Fisher (*op. cit.*) utilised Jeans' (1978) stratigraphy in which, as shown by Warrington and Scrivener (1980), corroborated by a study by Gallois (2001), part of the succession that includes the Arden Sandstone is duplicated. The Branscombe Mudstone Formation has proved largely devoid of palynomorphs; miospores, possibly of Norian (mid Late Triassic) age, are recorded only from the highest *c.* 37 m (Warrington, 2002). Palynomorph preparations from the Blue Anchor Formation include miospores, organic-walled microplankton and test-linings of foraminifers (Warrington, 1971, 1997, 2002; Stevenson and Warrington, 1971; Orbell, 1973; Fisher, 1985). The miospore associations from the upper *c.* 17 m are indicative of a Rhaetian (late Late Triassic) age (Warrington, 2002). The organic-walled microplankton are predominantly acritarchs (*Micrhystridium* spp., *Veryhachium* sp.) but include sporadic prasinophyte algae (*Tasmanites*) and possibly *Rhaetogonyaulax rhaetica*, a dinoflagellate cyst (Warrington, 1997).

The Penarth Group comprises the Westbury and overlying Lilstock formations, the latter divided into lower (Cotham) and upper (Langport) members. These units are fossiliferous and have yielded palynomorph assemblages and micro- and macrofaunal associations of Rhaetian (late Late Triassic) age. Palynomorphs recovered from the coast sections (Orbell, 1973; Fisher, 1985) and the nearby Lyme Regis (Warrington, 1997) and Charmouth 16A (Warrington, 2005) boreholes include miospores and organic-walled microplankton. The latter include *Rhaetogonyaulax rhaetica*, indicating the Rr dinoflagellate cyst zone *sensu* Powell (1992), which was regarded as Rhaetian, with its top, at the highest occurrence of *R. rhaetica*, marking the base of the Jurassic. However, *R. rhaetica* ranges into the basal Hettangian (Warrington, 1981, *in* Hounslow *et al*., 2004). Microfossils include ostracods and conodonts, recorded from the Cotham and Langport members respectively; macrofaunas are generally dominated by bivalves (Richardson, 1906; Swift and Martill, 1999).

The appearance of the ammonite *Psiloceras* is used to mark the base of the Hettangian, the lowest stage of the Jurassic System, in Britain. On the south Devon coast this occurs *c*. 2.5 m above the top of the Penarth Group, in Bed H.25 (Lang, 1924) of the Blue Lias Formation, the lowest beds of which are, therefore, assigned a latest Rhaetian age. Page (2002) retained a level in Bed H.25 as the base of the Jurassic, but suggested that psiloceratid ammonites from beds H.25 and 26 may be *Neophyllites*, indicating a broad correlation with the *imitans* and *antecedens* biohorizons of Page and Bloos (1998).

Summary

Understanding of the chronology of Permian and Triassic rocks in south-west England has advanced considerably in recent years. Isotopic age dating is applicable to only a small (Early Permian) part of the succession. Biostratigraphy is applicable in younger (Mid Permian and Mid and Late Triassic) parts of the succession, and magnetostratigraphy is, potentially, applicable throughout. Parts of the succession currently lack necessary data or have yielded equivocal or conflicting results. For example, palynological and magnetostratigraphic evidence indicate that the upper part of the Exeter Group is Mid Permian in age, possibly no younger than Wordian. However, vertebrate footprints from the highest formation have been regarded as 'Later Permian'; this instance may simply reflect a currently incomplete knowledge of the stratigraphical range of those ichnofossils. A number of Permian and Triassic stages lack GSSPs which results, even where sufficient information is available from the succession in south-west England, in an ability to assign only an approximate position to a correlative level. For example, prior to the ratification of the Ladinian GSSP in 2005, the base of that stage was, on magnetostratigraphical evidence, either in the higher part of the Otter Sandstone Formation or the lower part of the Sidmouth Mudstone Formation.

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References

BAUD, A. 1992. Vote of the subcommission members. *Albertiana*, **10**, 10.

BENTON, M. J., COOK, E. and TURNER, P. 2002. *Permian and Triassic Red Beds and the Penarth Group of Great Britain*. Geological Conservation Review Series, **24**. Joint Nature Conservation Committee, Peterborough.

BRISTOW, C. M. 2004. *Cornwall's Geology and Scenery* (2nd edition). Cornish Hillside Publications, St Austell.

BURLEY, S. D. and CORNFORD, C. 1998. Carbonate cements constrain the burial history of the Portledge-Peppercombe Permian outlier, north Devon. *Geoscience in south-west England*, **9**, 188-202.

BUTLER, M. 1998. The geological history of the southern Wessex Basin - a review of new information from oil exploration. In: UNDERHILL, J. R. (Ed.), *The Development, Evolution and Petroleum Geology of the Wessex Basin*. Geological Society, London, Special Publication, **133**, 67-86

CLAYDEN, A. W. 1908a. Note of the discovery of footprints in the "Lower Sandstones" of the Exeter district. *Report and Transactions of the Devonshire Association for the Advancement of Science*, **40**, 172-173.

CLAYDEN, A. W. 1908b. On the occurrence of footprints in the Lower Sandstones of the Exeter district. *Quarterly Journal of the Geological Society of London*, **64**, 496-500.

CLEGG, J. A., ALMOND, M. and STUBBS, P. H. S. 1954. The remanent magnetism of some sedimentary rocks in Britain. *Philosophical Magazine*, **45**, 583-598.

COCKS, L. R. M. 1993. Triassic pebbles, derived fossils and the Ordovician to Devonian palaeogeography of Europe. *Journal of the Geological Society, London*, **150**, 219-226.

CORNWELL, J. D. 1967. Palaeomagnetism of the Exeter Lavas, Devonshire. *Geophysical Journal of the Royal Astonomical Society*, **12**, 181-196.

CREER, K. M. 1957a. The remanent magnetization of unstable Keuper Marls. *Philosophical Transactions of the Royal Society of London*, **A.250**, 130-143.

CREER, K. M. 1957b. The natural remanent magnetization of certain stable rocks from Great Britain. *Philosophical Transactions of the Royal Society of London*, **A.250**, 111-129.

CREER, K. M., IRVING, E. and RUNCORN, S. K. 1957. Geophysical interpretation of palaeomagnetic directions from Great Britain. *Philosophical Transactions of the Royal Society of London*, **A.250**, 144-156.

EDWARDS, R. A., WARRINGTON, G., SCRIVENER, R. C., JONES, N. S., HASLAM, H. W. and AULT, L. 1997. The Exeter Group, south Devon, England: a contribution to the early post-Variscan stratigraphy of northwest Europe. *Geological Magazine*, **134**, 177-197.

EDWARDS, R. A. and SCRIVENER, R. C. 1999. *Geology of the country around Exeter*. Memoir of the British Geological Survey, 1:50 000 geological sheet 325 (England and Wales). The Stationery Office, London.

FISHER, M. J. 1972. The Triassic palynofloral succession in England. *Geoscience and Man*, **4**, 101-109.

FISHER, M. J. 1985. Palynology of sedimentary cycles in the Mercia Mudstone and Penarth groups (Triassic) of southwest and central England. *Pollen et Spores*, **27**, 95-122.

GALLOIS, R. W. 2001. The lithostratigraphy of the Mercia Mudstone Group (Mid to Late Triassic) of the south Devon coast. *Geoscience in south-west England*, **10**, 195-204.

GAYER, R. A. and CORNFORD, C. 1992. The Portledge-Peppercombe Permian outlier. *Proceedings of the Ussher Society*, **8**, 15-18.

HENSON, M. R. 1970. The Triassic rocks of south Devon. *Proceedings of the Ussher Society*, **2**, 172-177.

HOUNSLOW, M. W., McINTOSH, G., HAWKINS, R., EDWARDS, R. A. and WARRINGTON, G. 1998. The magnetostratigraphy of the Aylesbeare Mudstone Group, Devon, U.K. (Abstract: Epicontinental Triassic International Symposium Halle 1998). *Hallesches Jahrbuch für Geowissenschaften*, B.5, 79.

HOUNSLOW, M. W., McINTOSH, G., EDWARDS, R. A. and WARRINGTON, G. 2000. A magnetostratigraphic study of the Permo-Trias of south Devon. *Abstracts volume, Ussher Society Annual Meeting, Torquay, 2000.*

HOUNSLOW, M. W., POSEN, P. and JENKINS, G. 2001. Magnetostratigraphy of the Middle and Upper Triassic: Mercia Mudstone Group, south Devon, UK. *Abstracts volume, European Geophysical Society meeting, Nice, 2001*.

HOUNSLOW, M. W., GALLOIS, R., McINTOSH, G. and JENKINS, G. 2003. An Anisian, Ladinian, Carnian and basal Norian non-marine Triassic reference section: the coastal exposures between Budleigh Salterton and Branscombe, south Devon, U.K. (Abstract). *Geoscience in south-west England*, **10**, 453.

HOUNSLOW, M. W. and McINTOSH, G. 2003. Magnetostratigraphy of the Sherwood Sandstone Group (Lower and Middle Triassic), south Devon, UK: detailed correlation of the marine and non-marine Anisian. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **193**, 325-348.

HOUNSLOW, M. W., POSEN, P. E. and WARRINGTON, G. 2004. Magnetostratigraphy and biostratigraphy of the Upper Triassic and lowermost Jurassic succession, St. Audrie's Bay, UK. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **213**, 331- 358.

HOWARD, A. S., WARRINGTON, G., AMBROSE, K. and REES, J. G. *in press*. A formational framework for the Mercia Mudstone Group of England and Wales. *British Geological Survey Research Report*. British Geological Survey, Keyworth, Nottingham.

JEANS, C. V. 1978. The origin of the Triassic clay assemblages of Europe with special reference to the Keuper Marl and Rhaetic of parts of England. *Philosophical Transactions of the Royal Society of London*, **A.289**, 549-639.

JIN YUGAN, WARDLAW, B. R., GLENISTER, B. F. and KOTLYAR, G. V. 1997. Permian chronostratigraphic subdivisions. *Episodes*, **20**, 10-15.

LAMING, D. J. C. 1966. Imbrication, paleocurrents and other sedimentary features in the Lower New Red Sandstone, Devonshire, England. *Journal of Sedimentary Petrology*, **36**, 940-959.

LAMING, D. J. C. 1970. A guide to the New Red Sandstone of Tor Bay, Petitor and Shaldon. *Report and Transactions of the Devonshire Association for the Advancement of Science*, **101**, 207-218.

LANG, W. D. 1924. The Blue Lias of the Devon and Dorset coasts. *Proceedings of the Geologists' Association*, **35**, 169-185.

LEVERIDGE, B. E., HOLDER, M. T., GOODE, A. J. J., SCRIVENER, R. C., JONES, N. S. and MERRIMAN, R. J. 2002. *Geology of the Plymouth and south-east Cornwall area*. Memoir of the British Geological Survey, 1:50 000 geological sheet 348 (England and Wales). The Stationery Office, London.

LEVERIDGE, B. E., SCRIVENER, R. C., GOODE, A. J. J. and MERRIMAN, R. J. 2003. Geology of the Torquay district - a brief explanation of the geological map. *Sheet Explanation of the British Geological Survey*. 1: 50 000 Sheet 350 Torquay (England and Wales). British Geological Survey, Keyworth, Nottingham.

McKEEVER, P. J. and HAUBOLD, H. 1996. Reclassification of vertebrate trackways from the Permian of Scotland and related forms from Arizona and Germany. *Journal of Paleontology*, **70**, 1011-1022.

MENNING, M. 1995. A numerical time scale for the Permian and Triassic periods: an integrated time analysis. In: SCHOLLE, P. A., PERYT, T. M. and ULMER-SCHOLLE, D. S. (eds), *The Permian of northern Pangea*. Springer-Verlag, Berlin. Volume 1, 77-97.

MENNING, M. 2001. A Permian Time Scale 2000 and correlation of marine and continental sequences using the Illawara Reversal (265 Ma). *Natura Bresciana, Monografia*, **25**, 355-362.

MILLER, J. A., SHIBATA, K. and MUNRO, M. 1962. The potassium-argon age of the lava of Killerton Park, near Exeter. *Geophysical Journal of the Royal Astronomical Society*, **6**, 394-396.

MILLER, J. A. and MOHR, P. A. 1964. Potassium-argon measurements on the granites and some associated rocks from southwest England. *Geological Journal*, **4**, 105-126.

MILNER, A. R., GARDINER, B. G., FRASER, N. C. and TAYLOR, M. A. 1990. Vertebrates from the Middle Triassic Otter Sandstone Formation of Devon. *Palaeontology*, **33**, 873-892.

OGG, J. G. 2004. The Triassic Period. In: GRADSTEIN, F. M., OGG, J. G. and SMITH, A. G. (eds), *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, 271-306.

OPDYKE, N. D. and CHANNELL, J. E. 1996. *Magnetic stratigraphy*. International Geophysical Series, 64. Academic Press, London.

ORBELL, G. 1973. Palynology of the British Rhaeto-Liassic. *Bulletin of the Geological Survey of Great Britain*, **44**, 1-44.

OWENS, B. 1972. A derived Lower Tournaisian miospore assemblage from the Permo-Triassic deposits of South Devon. *Compte Rendu, 7ème Congrès Internationale de Stratigraphie et de Géologie du Carbonifère (Krefeld, 1971)*, **1**, 359-365.

PAGE, K. N. 2002. A review of the ammonite faunas and standard zonation of the Hettangian and Lower Sinemurian succession (Lower Jurassic) of the east Devon coast (south west England). *Geoscience in south-west England*, **10**, 293-303.

PAGE, K. N. and BLOOS, G. 1998. The base of the Jurassic System in west Somerset, south-west England - new observations on the succession of ammonite faunas of the lowest Hettangian Stage. *Proceedings of the Ussher Society*, **9**, 231-235.

PATON, R. L. 1974. Capitosauroid labyrinthodonts from the Trias of England. *Palaeontology*, **17**, 253-289.

POLLARD, J. E. 1976. A problematical trace fossil from the Tor Bay Breccias of south Devon. Written discussion of paper taken as read. *Proceedings of the Geologists' Association*, **87**, 105-109.

POSEN, P., HOUNSLOW, M. W. and ANDREWS, J. E. 2001. High resolution analysis of cyclicity in Upper Triassic lake sediments in the UK. *Abstracts volume, European Union of Geosciences meeting, Strasbourg, April 2001*.

POWELL, A. J. 1992. Dinoflagellate cysts of the Triassic System. In: POWELL, A. J. (ed.), *A stratigraphic index of dinoflagellate cysts*. Chapman & Hall, London, 1-6.

PURVIS, K. and WRIGHT, V. P. 1991. Calcretes related to phreatophytic vegetation from the Middle Triassic Otter Sandstone of south west England. *Sedimentology*, **38**, 538-551.

RICHARDSON, L. 1906. On the Rhaetic and contiguous deposits of Devon and Dorset. *Proceedings of the Geologists' Association*, **19**, 401-409.

RIDGWAY, J. M. 1974. A problematical trace fossil from the New Red Sandstone of south Devon. *Proceedings of the Geologists' Association*, **85**, 511-517.

SCRIVENER, R. C. 1994. Presidential address: aspects of Devon geology from Pengelly to the present day. *Report and Transactions of the Devonshire Association for the Advancement of Science*, **126**, 1-16.

SELWOOD, E. B., EDWARDS, R. A., SIMPSON, S., CHESHER, J. A., HAMBLIN, R. J. O., HENSON, M. R., RIDDOLLS, B. W. and WATERS, R. A. 1984. *Geology of the country around Newton Abbot*. Memoir of the British Geological Survey, 1:50 000 geological sheet 339 (England and Wales). HMSO, London.

SHAPTER, T. 1842. *The climate of the south of Devon; and its influence on health: with short accounts of Exeter, Torquay, Babbacombe, Teignmouth, Dawlish, Exmouth, Budleigh-Salterton, Sidmouth, &c*. John Churchill, London.

SPENCER, P. S. and STORRS, G. W. 2002. A re-evaluation of small tetrapods from the Middle Triassic Otter Sandstone Formation of Devon, England. *Palaeontology*, **45**, 447-467.

STEVENSON, C. R. and WARRINGTON, G. 1971. Jurassic and Cretaceous rocks of Wessex: highest Keuper deposits. Written discussion to report of field meeting. *Proceedings of the Geologists' Association*, **82**, 297-300.

SWIFT, A. and MARTILL, D. W. 1999. Fossils of the Rhaetian Penarth Group. *Palaeontological Association Field Guides to Fossils*, **9**. The Palaeontological Association, London.

THOMAS, R. G. 2003. Report on the discovery of a coprolite in Permian redbeds near Kingsand, Cornwall (Abstract). *Geoscience in south-west England*, **10**, 450.

WAGER, L. R. 1964. The history of attempts to establish a quantitative time-scale. In: HARLAND, W. B., SMITH, W. G. and WILCOCK, B. (eds), *The Phanerozoic Time-scale*. The Geological Society, London, 13-28.

WARDLAW, B. R., DAVYDOV, V. and GRADSTEIN, F. M. 2004. The Permian Period. In: GRADSTEIN, F. M., OGG, J. G. and SMITH, A. G. (eds), *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, 249-270.

WARRINGTON, G. 1971. Palynology of the New Red Sandstone sequence of the south Devon coast. *Proceedings of the Ussher Society*, **2**, 307-314

WARRINGTON, G. 1981. The indigenous micropalaeontology of British Triassic shelf seas. In: NEALE, J. W. and BRASIER, M. D. (eds), *Microfossils from Recent and fossil shelf seas*. Ellis Horwood Limited, Chichester, 61-70.

WARRINGTON, G. 1997. The Lyme Regis Borehole, Dorset - palynology of the Mercia Mudstone, Penarth and Lias groups (Upper Triassic - Lower Jurassic). *Proceedings of the Ussher Society*, **9**, 153-157.

WARRINGTON, G. 2002. Palynology of the Late Triassic and earliest Jurassic succession (Mercia Mudstone and Penarth groups, and the basal Lias): south-east Devon and south-west Dorset (Abstract). *Geoscience in south-west England*, **10**, 377

WARRINGTON, G. 2004. Red rocks of the west – the tip of the 'iceberg'. *OUGS Journal*, **25**, 28-32.

WARRINGTON, G. 2005. The Charmouth 16A borehole, Dorset, U.K.: palynology of the Penarth Group and basal Lias Group (Upper Triassic-Lower Jurassic). *Geoscience in south-west England*, **11**, 109-116.

WARRINGTON, G. AUDLEY-CHARLES, M. G., ELLIOTT, R. E., EVANS, W. B., IVIMEY-COOK, H. C., KENT, P. E., ROBINSON, P. L., SHOTTON, F. W. and TAYLOR, F. M. 1980. *A correlation of Triassic rocks in the British Isles*. Geological Society, London, Special Report, **13**.

WARRINGTON, G. and SCRIVENER, R. C. 1980. The Lyme Regis (1901) Borehole succession and its relationship to the Triassic sequence of the east Devon coast. *Proceedings of the Ussher Society*, **5**, 24-32.

WARRINGTON, G. and SCRIVENER, R. C. 1988. Late Permian fossils from Devon: regional geological implications. *Proceedings of the Ussher Society*, **7**, 95-96.

WARRINGTON, G. and SCRIVENER, R. C. 1990. The Permian of Devon, England. *Review of Palaeobotany and Palynology*, **66**, 263-272.

WRIGHT, V. P., MARRIOTT, S. B. and VANSTONE, S. D. 1991. A 'reg' palaeosol from the Lower Triassic of south Devon: stratigraphic and palaeoclimatic implications. *Geological Magazine*, **128**, 517-523.

ZIJDERVELD, J. D. A. 1967. The natural remanent magnetizations of the Exeter Volcanic Traps (Permian, Europe). *Tectonophysics*, **4**, 121-153.